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A review of solar-powered Stirling engines and low temperature differential Stirling engines

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Abstract

This article provides a literature review on solar-powered Stirling engines and low temperature differential Stirling engines technology. A number of research works on the development of Stirling engines, solar-powered Stirling engines, and low temperature differential Stirling engines is discussed. The aim of this review is to find a feasible solution which may lead to a preliminary conceptual design of a workable solar-powered low temperature differential Stirling engine.

Results from the study indicate that Stirling engines working with relatively low temperature air are potentially attractive engines of the future, especially solar-powered low temperature differential Stirling engines with vertical, double-acting, gamma-configuration.

Keywords: Stirling engine; Hot-air engine; Solar-powered heat engine

Contents

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1. Introduction

Solar energy is one of the more attractive renewable energy sources that can be used as an input energy source for heat engines. In fact, any heat energy source can be used with the Stirling engine. The solar radiation can be focused onto the displacer hot-end of the Stirling engine, thereby creating a solar-powered prime mover. The direct conversion of solar power into mechanical power reduces both the cost and complexity of the prime mover. In theory, the principal advantages of Stirling engines are their use of an external heat source and their high efficiency. Stirling engines are able to use solar energy that is a cheap source of energy. Since during two-thirds of the day, solar energy is not available, solar/fuel hybrids are needed.

Since the combustion of the Stirling engine is continuous process, it can burn fuel

more completely and is able to use all kinds of fuel with any quality. Because of its simple construction, and its manufacture being the same as the reciprocating internal combustion engine, and when produced in a large number of units per year, the Stirling engine would obtain the economy of scale and could be built as a cheap power source for developing countries. For solar electric generation in the range of 1–100 kW_e, the Stirling engine was considered to be the cheapest [1]. Although the Stirling engine efficiency may be low, reliability is high and costs are low. Moreover, simplicity and reliability are keys to a cost effective Stirling solar generator.

The objective of this article is to provide a basic background and review of existing literature on solar-powered Stirling engines and low temperature differential Stirling engine technology. A number of Stirling engine configurations and designs, including the engine's development, are provided and discussed. It is hoped that this article will be useful in discovering feasible solutions that may lead to a preliminary conceptual design of a solar-powered low temperature differential Stirling engine.

2. General principles

Stirling engines are mechanical devices working theoretically on the Stirling cycle, or its modifications, in which compressible fluids, such as air, hydrogen, helium, nitrogen or even vapors, are used as working fluids. The Stirling engine offers possibility for having high efficiency engine with less exhaust emissions in comparison with the internal combustion engine. The earlier Stirling engines were huge and inefficient. However, over a period of time, a number of new Stirling engine models have been developed to improve the deficiencies.

The modern Stirling engine is more efficient than the early engines and can use any high temperature heat source. The Stirling engine is an external combustion engine. Therefore, most sources of heat can power it, including combustion of any combustible material, field waste, rice husk or the like, biomass methane and solar energy. In principle, the Stirling engine is simple in design and construction, and can be operated easily.

Direct solar-powered Stirling engines may be of great interest to countries where solar energy is available in unlimited quantity. To use direct solar energy, a solar concentrator and absorber must be integrated with the engine system.

The Stirling engine could be used in many applications and is suitable where [2]:

1. multi-fueled characteristic is required;
2. a very good cooling source is available;
3. quiet operation is required;
4. relatively low speed operation is permitted;
5. constant power output operation is permitted;
6. slow changing of engine power output is permitted;
7. a long warm-up period is permitted.

2.1. Stirling engine configurations

2.1.1. Mechanical configurations of the Stirling engine

Various machine components have been combined to provide the Stirling cycle. The cycle provides a constant-volume process during the transfer of working fluid between the hot and cold space of the engine, and provides a constant-temperature heating and cooling process during compression and expansion. The compression and expansion processes of the cycle generally take place in a cylinder (called power cylinder) with a piston (called power piston). A displacer piston (simply called displacer) shuttles the working fluid back and forth through the heater, regenerator, and cooler at constant volume. As shown in Fig. 1, a displacer that moves to the cold space, displaces the working fluid from the cold space causing it to flow to the hot space and vice versa. Three different configurations, namely the alpha-, beta-, and gamma-configurations, are commonly used. Each configuration has the same thermodynamic cycle but has different mechanical design characteristics [1].

In the alpha-configuration a displacer is not used. Two pistons, called the hot and cold pistons, are used on either side of the heater, regenerator, and cooler. These pistons move uniformly in the same direction to provide constant-volume heating or cooling processes of the working fluid. When all the working fluid has been transferred into one cylinder, one piston will be fixed and the other piston moves to expand or compress the working fluid. The expansion work is done by the hot piston while the compression work is done by the cold piston [1].

In the beta-configuration, a displacer and a power piston are incorporated in the same cylinder. The displacer moves working fluid between the hot space and the cold space of the cylinder through the heater, regenerator, and cooler. The power piston, located at the cold space of the cylinder, compresses the working fluid when the working fluid is in the cold space and expands the working fluid when the working fluid is moved into the hot space [1].

The gamma-configuration uses separated cylinders for the displacer and the power

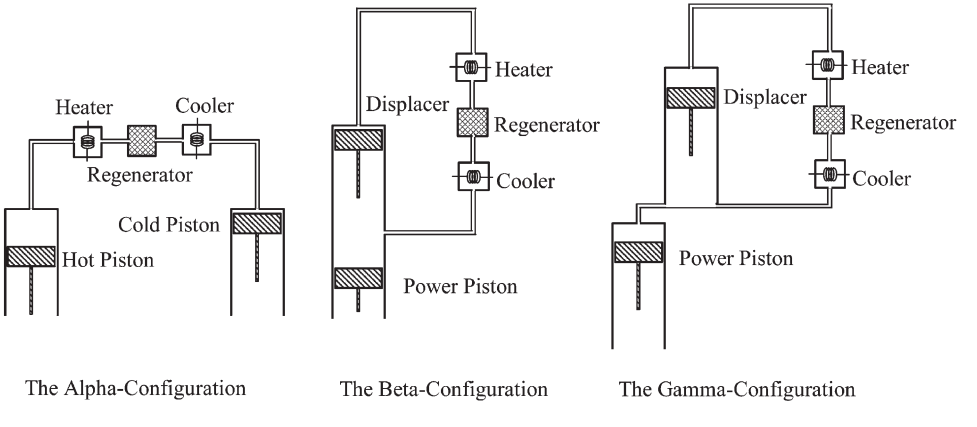

Fig. 1. Three basic mechanical configurations for Stirling engine.

pistons, with the power cylinder connected to the displacer cylinder. The displacer moves working fluid between the hot space and the cold space of the displacer cylinder through the heater, regenerator, and cooler. In this configuration, the power piston both compresses and expands the working fluid. The gamma-configuration with double-acting piston arrangement has theoretically the highest possible mechanical efficiency. This configuration also shows good self-pressurization [3]. However, the engine cylinder should be designed in vertical type rather than horizontal in order to reduce bushing friction [4].

2.1.2. Low temperature differential engine configurations

A low temperature differential (LTD) Stirling engine can be run with small temperature difference between the hot and cold ends of the displacer cylinder [5]. It is different from other types of Stirling-cycle engines, which have a greater temperature difference between the two ends, and therefore the power developed from the engine can be greater.

LTD engines may be of two designs. The first uses single-crank operation where only the power piston is connected to the flywheel, called the Ringbom engine. This type of engine, that has been appearing more frequently, is based on the Ringbom principle. A short, large-diameter displacer rod in a precise-machined fitted guide has been used to replace the displacer connecting rod [5]. The other design is called a kinematic engine, where both the displacer and the power piston are connected to the flywheel. The kinematic engine with a normal 90° phase angle is a gamma-configuration engine [5].

Some characteristics of the LTD Stirling engine [5] are as follows.

1. Displacer to power piston swept volumes ratio is large;
2. diameter of displacer cylinder and displacer is large;
3. displacer is short;
4. effective heat transfer surfaces on both end plates of the displacer cylinder are large;
5. displacer stroke is small;
6. dwell period at the end of the displacer stroke is rather longer than the normal Stirling engine;
7. operating speed is low.

LTD Stirling engines provide value as demonstration units, but they immediately become of interest when considering the possibility of power generation from many low temperature waste heat sources in which the temperature is less than 100 °C [2]. A calculation using the Carnot cycle formula shows that an engine operating with a source temperature of 100 °C and a sink temperature of 35 °C gives a maximum thermal efficiency of about 17.42%. If an engine could be built for achieving 50% of the maximum thermal efficiency, it would have about 8.71% overall Carnot efficiency. Even the calculated thermal efficiency seems rather low, but LTD Stirling engines could be used with free or cheap low temperature sources. This engine should be selected when the low cost engines are put into consideration.

Although the specific power developed by LTD Stirling engines is low, lightweight and cheap materials such as plastics can be used as engine parts.

2.2. Principle of operation

The Stirling hot air engine is a simple type of engine that uses a compressible fluid as the working fluid. Because the working fluid is in a closed system, there are no problems with contamination and working fluid costs. Heat transfer to the working fluid is very important. High mass flow is needed for good heat transfer. The working fluid should be that of low viscosity to reduce pumping losses. Using higher pressure or lower viscosity, or combinations thereof, could reduce the high mass flow required.

The Stirling engine could theoretically be a very efficient engine in upgrading from heat to mechanical work with the Carnot efficiency. The thermal limit of the operation of the Stirling engine depends on the material used for construction. Engine efficiency ranges from about 30 to 40% resulting from a typical temperature range of 923–1073 K, and a normal operating speed range from 2000 to 4000 rpm [1].

2.2.1. Stirling cycle

The ideal Stirling cycle has three theoretical advantages. First, the thermal efficiency of the cycle with ideal regeneration is equal to the Carnot cycle. During the transfer strokes, the regenerator, which is a typical temporary energy storage, rapidly absorbs and releases heat to the working fluid which is passing through. Therefore, the quantity of heat taken from the external heat source is reduced, this results in improving the thermal efficiency (Fig. 2).

The second advantage, over the Carnot cycle, is obtained by substitution of two isentropic processes with two constant-volume processes. This results in increasing the *p*–*v* diagram area. Therefore, a reasonable amount of work from the Stirling cycle is obtained without the necessity to use very high pressures and large swept

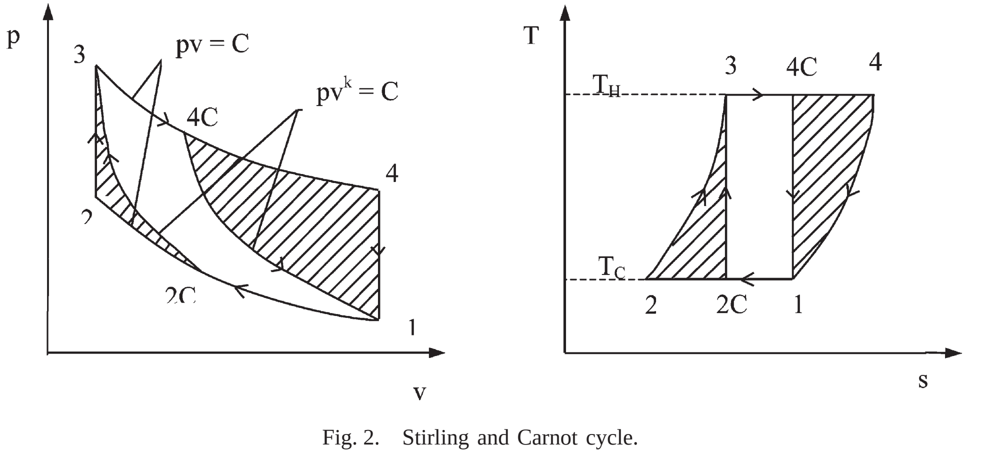

Fig. 2. Stirling and Carnot cycle.

volumes, as in the Carnot cycle. The Stirling cycle compared with the Carnot cycle between the same given limits of pressure, volume, and temperature, is shown in Fig. 2. The shaded areas 2C-2-3 and 1-4C-4 indicate the additional work available by replacing two isentropic processes with two constant-volume processes. The Carnot cycle isothermal processes (1-2C and 3-4C) are, respectively, extended to process 1–2 and 3–4. The amount of available work is increased in the same proportion as the heat supplied to—and rejected from—the Stirling cycle [10].

The third advantage has recently been discovered. Compared with all reciprocal piston heat engines working at the same temperature limits, the same volume ratios, the same mass of ideal working fluid, the same external pressure, and mechanism of the same overall effectiveness, the ideal Stirling engine has the maximum possible mechanical efficiency [3]. These three advantages reveal that the Stirling engine is a theoretical equivalent of all heat engines [3].

2.2.1.1. Stirling engine operation [5] Isothermal compression process 1–2 (heat transfer from working fluid at low temperature to an external sink): After the displacer has pushed the working fluid into the cold space of the cylinder, where it was cooled, it was then held stationary at its top dead center (TDC) (Fig. 3). This indicated the state 1 and the pressure at this state is p_1. The power piston is then being pushed from bottom dead center (BDC) to TDC by flywheel momentum helped by partial vacuum created by the cooling working fluid. The working fluid is in the cold space and is under compression by power piston, which is approaching TDC, and compressing working fluid from 1 to 2 at constant temperature. The work done on the working fluid indicated by the area under process 1–2.

Constant-volume heating process 2–3 (heat transfer to the working fluid from regenerator): The displacer is moving from TDC to BDC and transferring working fluid from the cold space to the hot space, while the power piston remains stationary at its TDC, awaiting increase in pressure as a result of expanding working fluid. The displacer is pushing the working fluid into the hot space, passing through a regenerator which has stored heat, and already a certain amount is being heated. Heat given up by the regenerator raises the temperature and pressure of the working fluid from 2 to 3 at constant volume. Heat stored in the regenerator is added to the working fluid.

Isothermal expansion process 3–4 (heat transfer to the working fluid at high temperature supplied by an external source): After the displacer has pushed all the working fluid into the hot space, with a corresponding increase in pressure to the maximum, it is then kept at rest at its BDC. The working fluid is in the hot space and is expanding to pressure p_4, while a constant temperature process 3–4 is maintained applied at the hot space. The power piston is being pushed from TDC to BDC by the increased pressure, and is applying force to the flywheel, thus creating mechanical energy. This energy will be utilized throughout the remaining processes of the cycle. The work done by the working fluid is indicated by the area under process 3–4.

Constant-volume cooling process 4–1 (heat transfer from the working fluid to the regenerator): After the power piston has reached its BDC and has supplied its energy to the flywheel, it remains stationary and is ready to travel back to TDC under

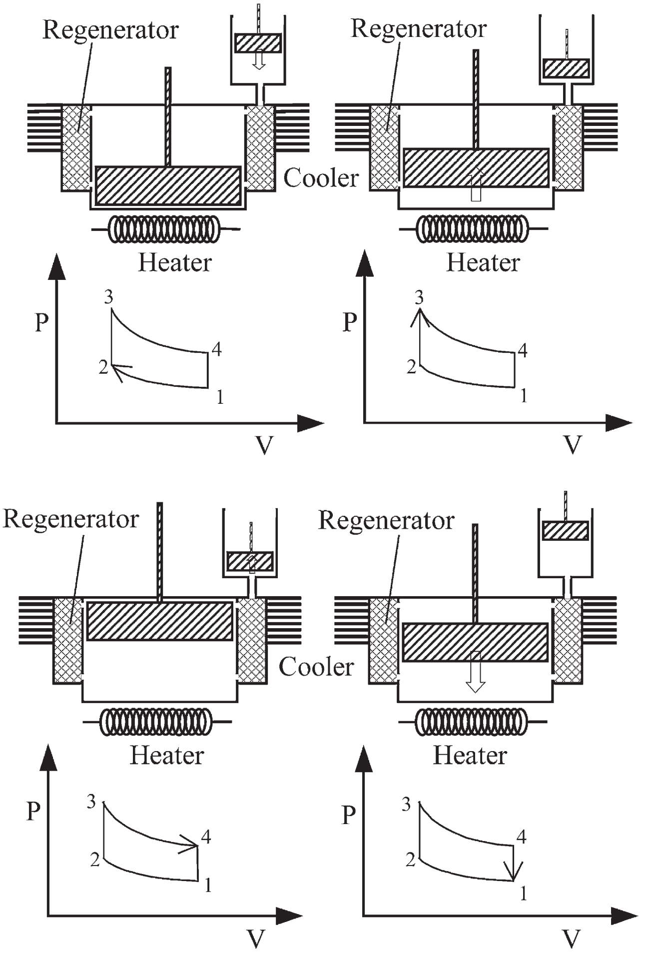

Fig. 3. Stirling engine operation.

flywheel momentum and the sucking action of the partial vacuum created by the falling pressure. The displacer is moving from BDC to TDC and is transferring working fluid to the cold space where the pressure will fall and a partial vacuum is created, through the regenerator, causing a fall in temperature and pressure of the working fluid from 4 to 1 at constant volume. Heat is transferred from the working fluid to the regenerator.

2.2.1.2. Motion diagram The movement of the power piston and the displacer require an out-of-phase motion. There is a calculated gap both in time and in motion—then the displacer and the power piston do not move backwards and forwards at the same time. To obtain this out-of-phase motion, this gap should be a 90° phase angle, with the stroke of the displacer always leading the power piston

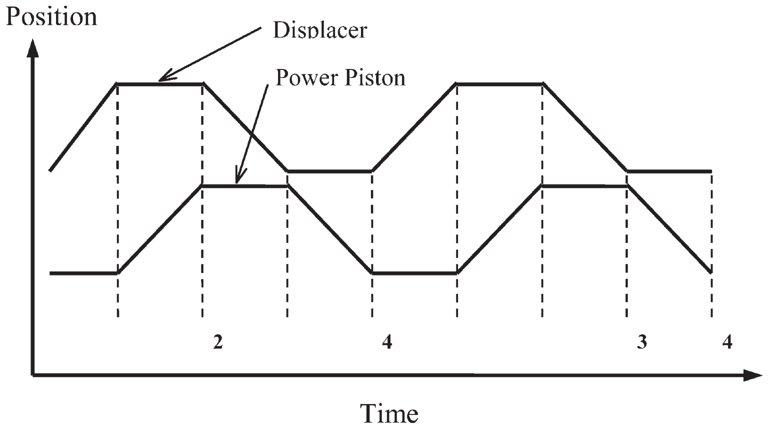

Fig. 4. Ideal motion diagram of a gamma-configuration Stirling engine.

by approximately 90°. The function of the displacer is to transfer working fluid from one end of the cylinder to the other. The function of the power piston is to convert the expansion of working fluid at high pressure and compression of working fluid at low temperature and to transfer this conversion into motion by means of a crankshaft and flywheel [5]. Fig. 4 shows the ideal motions of a gamma-configuration Stirling engine and Fig. 5 shows how well sinusoidal motion can fit the ideal motion [3].

2.2.2. Stirling cycle efficiency

For an air-standard Stirling cycle, the amounts of heat added and rejected per unit mass of working fluid are as follows [6]:

$$Q_{\text{added}} = xc_{\text{v}}(T_{\text{H}}-T_{\text{C}}) + RT_{\text{H}} \ln v_1/v_2 \quad (1)$$

$$Q_{\text{rejected}} = xc_{\text{v}}(T_{\text{C}}-T_{\text{H}}) + RT_{\text{C}} \ln v_2/v_1 \quad (2)$$

where x is the fractional deviation from ideal regeneration (i.e. $x = 1$ for no regener-

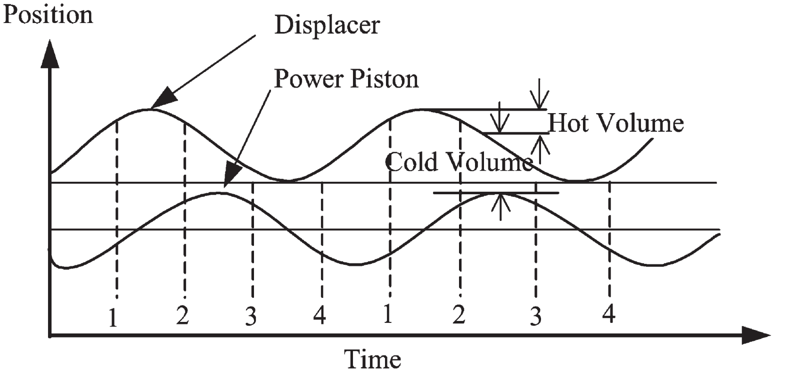

Fig. 5. Sinusoidal motion diagram of a gamma-configuration Stirling engine with a 90° phase angle.

ation and $x = 0$ for ideal regeneration), c_v the specific heat capacity at constant volume in J/(kg K), T_H the source temperature in the Stirling cycle in K, T_C the sink temperature in K, R the gas constant in J/(kg K), v_1 and v_2 are specific volumes of the constant-volume regeneration processes of the cycle in m^3/kg, and v_2/v_1 is the volume compression ratio. The Stirling cycle efficiency can be expressed as [6]:

$$\eta_S = \frac{\Sigma Q}{Q_{added}} = \frac{(T_H - T_C) R \ln v_1/v_2}{x c_v (T_H - T_C) + R T_H \ln v_1/v_2}$$

then

$$\eta_S = \frac{1 - T_C/T_H}{1 + (x c_v / R \ln v_1/v_2)(1 - T_C/T_H)} \tag{3}$$

or

$$\eta_S = \frac{1 - 1/\theta}{1 + C_S(1 - (1/\theta))} \tag{4}$$

where

$$\theta = T_H/T_C \tag{5}$$

and

$$C_S = x c_v / [R \ln v_1/v_2] \tag{6}$$

2.2.3. Engine indicated work

2.2.3.1. Schmidt formula Schmidt [7] showed a mathematically exact expression for determining the indicated work per cycle of a Stirling engine. The Schmidt formula may be shown in various forms depending on the notations used. Because of its complexity, it takes time to verify the calculation [3]. The calculation for gamma-configuration Stirling engines is as follows [8]:

$$W_{Schmidt} = \pi(1-\tau) p_{max} V_D \frac{k_P \sin\alpha}{Y + \sqrt{Y^2 - X^2}} \sqrt{\frac{Y - X}{Y + X}} \tag{7}$$

where:

$$k_P = V_P/V_D \tag{8}$$

$$V_D = A_D L_D \tag{9}$$

$$V_P = A_P L_P \tag{10}$$

$$X = \sqrt{(1-\tau)^2 - 2(1-\tau) k_P \cos\alpha + k_P^2} \tag{11}$$

$$Y = 1 + \tau + \frac{4 k_S \tau}{1 + \tau} + k_P \tag{12}$$

$$\tau = T_C/T_H \tag{13}$$

$$k_S = V_S/V_D \tag{14}$$

where $W_{Schmidt}$ is the indicated work per cycle in N m, p_{max} the maximum pressure attained during cycle in N/m^2, k_P the swept volume ratio, k_S the dead space volume ratio, V_D the displacer swept volume in m^3, V_P the power piston swept volume in m^3, V_S the dead space volume in m^3, A_D the displacer cylinder cross-section area in m^2, A_P the power cylinder cross-section area in m^2, L_D the displacer stroke in m, L_P the power piston stroke in m, α the phase angle lead of the displacer over the power piston in degrees, and τ is the temperature ratio.

Because it is more convenient to use the mean or average cycle pressure, p_m, instead of the maximum cycle pressure, p_{max}, the maximum pressure under the Schmidt assumptions is related to the average cycle pressure [3]. It is as follows:

$$p_{max} = p_m\sqrt{\frac{Y+X}{Y-X}} \tag{15}$$

Substituting Eq. (15) into Eq. (7) gives the simpler form of the Schmidt formula for determining the indicated cyclic work of the gamma-configuration Stirling engine:

$$W_{Schmidt} = \pi(1-\tau)p_m V_D \frac{k_P \sin\alpha}{Y+\sqrt{Y^2-X^2}} \tag{16}$$

2.2.3.2. West formula West [9] proposed a simpler formula to determine indicated work as follows:

$$W_{West} = \frac{\pi p_m}{2}\frac{V_D V_P}{V_D + \frac{V_P}{2} + V_S}\frac{(T_H-T_C)}{(T_H+T_C)}\sin\alpha \tag{17}$$

Eq. (17) gives an error of the indicated work for sinusoidal motion compared to the exact solution from Eq. (16). However, it is more popular because of its simplicity.

2.2.4. Engine power output

2.2.4.1. Beale formula Beale [10] noted that the power output of several Stirling engines observed could be calculated approximately from the equation:

$$P = 0.015 p_m f V_P \tag{18}$$

where P is the engine power output in Watts, p_m the mean cycle pressure in bar, f the cycle frequency in Hz, and V_P is displacement of power piston in cm^3. The Beale formula can be used for all configurations and for various sizes of Stirling engines. Eq. (18) may be written in a general form as follows:

$$P/(p_m f V_P) = \text{constant} \tag{19}$$

The resulting dimensionless parameter $P/(p_m f V_P)$ is called the Beale number. It is clear that the Beale number is a function of both source and sink temperatures. The

solid line in Fig. 6 indicates the relationship between the Beale number and source temperature. The upper bound represents the high efficiency, well-designed engines with low sink temperatures, while the lower bound represents the moderate efficiency, less well-designed engines with high sink temperatures [10].

2.2.4.2. Mean pressure power formula The Beale number correlation was modified by Walker [11], West [12], and Senft [13]. This correlation is used to determine the Stirling engine shaft power output as follows:

$$P = Fp_{m}fV_{P}\frac{T_{H}-T_{C}}{T_{H}+T_{C}} \tag{20}$$

Eq. (20) is a powerful tool in the first step of the design. Senft [13] proved that the factor F in Eq. (20) is 2 for the ideal Stirling cycle. However in this ideal cycle, F does not take into account the mechanical loss, friction etc. Senft [3] and West [9] described that an F value of 0.25–0.35 may be used for practical use.

A more accurate calculation of the shaft power than offered by the Beale formula that was used to initiate the preliminary design stage, can be made by using either the Schmidt or West formula. Martini [8] recommended that the shaft power could be obtained by reducing the Schmidt formula by an ‘experience factor’ of around 35% [3].

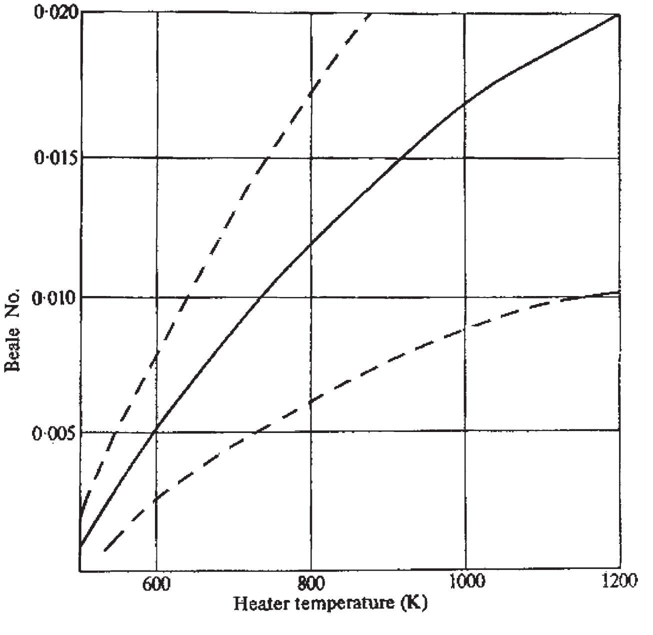

Fig. 6. Beale number as a function of source temperature. Source: Walker [10].

3. Development of Stirling engines

3.1. First era of Stirling engines

The Stirling engine was the first invented regenerative cycle heat engine. Robert Stirling patented the Stirling engine in 1816 (patent no. 4081). Engines based upon his invention were built in many forms and sizes until the turn of the century. Because Stirling engines were simple and safe to operate, ran almost silently on any combustible fuel, and were clean and efficient compared to steam engines, they were quite popular [3]. These Stirling engines were small and the power produced from the engine was low (100 W to 4 kW).

In 1853, John Ericsson built a large marine Stirling engine having four 4.2 m diameter pistons with a stroke of 1.5 m producing a brake power of 220 kW at 9 rpm [10]. The first era of the Stirling engine was terminated by the rapid development of the internal combustion engine and electric motor.

3.2. Second era of Stirling engines

The second era of the Stirling engine began around 1937 [3], when the Stirling engine was brought to a high state of technological development by the Philips Research Laboratory in Eindhoven, Holland, and has progressed continuously since that time. Initial work was focused on the development of small thermal-power electric generators for radios and similar equipment used in remote areas [3,4].

New materials were one of the keys to Stirling engine success. The Philips research team used new materials, such as stainless steel [3]. Another key to success was a better knowledge of thermal and fluid physics than in the first era. The specific power of the small '102C' engine of 1952 was 30 times that of the old Stirling engines [14].

The progress in further development made by Philips and many other industrial laboratories, together with the need for more energy resources, has sustained the second era of Stirling engine development until today [3].

3.3. Stirling engines for industries

Intensive research by Philips and industrial laboratories led to the development of small Stirling engines with high efficiencies of 30% or more. In 1954, Philips developed an engine using hydrogen as a working fluid. This engine produced 30 kW for a maximum cycle temperature of 977 K at 36% thermal efficiency. The efficiency of the same engine was later improved to 38%. The experimental studies of engines of various sizes up to 336 kW were studied [4].

Other attempts to further develop Stirling engines under license of Philips, were carried out by General Motors from 1958 to 1970 [10]. Other licenses were granted by Philips to United Stirling AB of Malmo, Sweden in 1968 and to the West German consortium of MAN and MWM in 1967 [10]. In 1973, the Philips/Ford 4-125 experimental automotive Stirling engine accomplished a specific power of over 300 times that of the early Stirling engines [3].

3.4. Stirling engines for rural and remote areas

Trayser and Eibling [15] carried out a design study to determine the technical feasibility of developing a 50 W portable solar-powered generator for use in remote areas. The results of their study indicates that it is possible to build ra solar-powered lightweight portable, reliable, Stirling engine at a reasonable cost.

Gupta et al. [16] developed 1 and 1.9 kW solar-powered reciprocating engines for rural applications. Engine efficiencies were found to be between 5.5 and 5.7% and overall efficiency was found to be 2.02% [17]. Pearch et al. [18] proposed and analyzed a 1 kW domestic, combined heat and power (DCHP) system. The results show that 30% of a home's electrical demand could be generated and electricity cost could be reduced by about 25%.

Podesser [19] designed, constructed and operated a Stirling engine, heated by the flue gas of a biomass furnace, for electricity production in rural villages. With a working gas pressure of 33 bar at 600 rpm and a shaft power of 3.2 kW, an overall efficiency of 25% was obtained. He expected to extend the shaft power to 30 kW in the next step.

Dixit and Ghodke [20] designed compact power generating systems capable of using the combination of a wide variety of solid fuels as a local power source. The system was a heat pipe-based, biomass energy-driven Stirling engine. The macroscopic thermal design of the engine along with the calculation of various energy losses was reported.

3.5. Stirling engine optimization

Usually the design point of a Stirling engine will be somewhere between the two limits of: (1) maximum efficiency point; and (2) maximum power point. Markman et al. [21] conducted an experiment using the beta-configuration of the Stirling engine to determine the parameters of a 200 W Stirling engine by measuring the thermal-flux and mechanical-power losses. The aim of the project was to optimize and increase the engine efficiency.

Orunov et al. [22] presented a method to calculate the optimum parameters of a single-cylinder Stirling engine. They concluded that mass and size characteristics of the engine could be improved by using the correct choice of the optimal parameters which would result in larger efficiency.

Abdalla and Yacoub [23] studied the feasibility of using waste heat from a refuse incinerator with a Stirling engine. Heat from incineration was used to power the desalination plant and the Stirling engine. Using saline feed raw water as the cooling water and by assuming 50% heat recovery efficiency, they claimed that the engine efficiency could be improved and a thermal efficiency of 27% was obtained.

Nakajima et al. [24] developed a 10 g micro Stirling engine with an approximately 0.05 cm^3 piston swept volume. An engine output power of 10 mW at 10 Hz was reported. The problems of scaling down were discussed.

Aramtummaphon [25] tested an open cycle Stirling engines by using steam heated from producer gas. The first engine produced an indicated power of about 1.36 kW

at a maximum speed of 950 rpm, while the second engine, improved from the first one, produced an indicated power of about 2.92 kW at a maximum speed of 2200 rpm.

Hirata et al. [26] evaluated the performance of a small 100 W displacer-type Stirling engine Ecoboy-SCM81. An analysis model using an isothermal method considering a pressure loss in the regenerator, a buffer space loss, and a mechanical loss for the prototype engine was developed to improve the engine performance. After the effectiveness of the analysis model was evaluated, some improvements for the prototype engine were discussed.

Costea and Feidt [27] studied the effect of the variation of the overall heat transfer coefficient on the optimum state and on the optimum distribution of the heat transfer surface conductance or area of the Stirling engine heat exchanger. The results pointed out either an optimum variation range for some model parameters, or some significant differences of the power output, source and sink temperature differences, heat transfer characteristic values with respect to each of the studied cases.

Wu et al. [28] analyzed the optimal performance of a Stirling engine. The influences of heat transfer, regeneration time and imperfect regeneration on the optimal performance of the irreversible Stirling engine cycle were discussed. The results of their work provided a new theoretical basis for evaluating performance and improving Stirling engines.

Wu et al. [29] studied the optimal performance of forward and reverse quantum Stirling cycles. The finite time thermodynamic performance bound, optimization criteria and sensitivity analysis were presented. The results showed that the quantum Stirling cycle was different from the classical thermodynamic one. This was because of the different characters of the working fluids.

Wu et al. [30] studied the finite-time exergoeconomic optimal performance of a quantum Stirling engine. The maximum exergoeconomic profit, the optimal thermal efficiency and power output corresponding to performance bound of an endoreversible quantum Stirling engine were presented. The result of this work showed a profit bound for designing a real Stirling engine working with a quantum fluid.

Gu et al. [31] attempted to design a high efficiency Stirling engine using a composite working fluid, e.g. two-component fluid: gaseous carrier and phase-change component and single multi-phase fluid, together with supercritical heat recovery process. The results were compared with those of common Stirling engines. The criteria for the choice of working fluid were discussed. Calculation by using sulfur hexafluoride as the working fluid was given as an example to show the thermal efficiency and optimum condensing pressure and temperature.

Winkler and Lorenz [32] described the integration of thin tubular solid oxide fuel cells (SOFCs) and heat engine system. The heat engines investigated were microturbines and Stirling engines. A high system efficiency, low specific volumes, and a small available unit of solid oxide fuel cells was expected from Stirling engine system. Further development for industrial projects was recommended.

Hsu et al. [33] studied the integrated system of a free-piston Stirling engine and an incinerator. The performance of a free-piston Stirling engine was investigated

using the averaged heat transfer model. The efficiency and the optimal power output, including the effect induced by internal and external irreversibility, were described.

Petrescu et al. [34] presented a method for calculating the efficiency and power of a Stirling engine. The method was based on the first law of thermodynamics for processes with finite speed and the direct method for closed systems. The results showed good agreement with the actual engine performance obtained from 12 different Stirling engines over a range from economy to maximum power output.

4. Development of solar-powered Stirling engines

4.1. Solar-powered Stirling engines in the first era

In 1864, Ericsson [5] invented a solar-powered hot air engine using a reflector to heat the displacer cylinder hot-end. Jordan and Ibele [35] reported that between 1864 and 1870, Ericsson used parabolic trough collectors to heat steam and used steam to drive his engine [36]. In 1870, the Stirling engine was adapted by Ericsson to operate with solar energy ([37] cited in Ref. [38]).

Spencer [36] reported that in 1872, Ericsson built an open-cycle hot-air engine using a spherical mirror concentrator. This engine was the first solar-powered hot air engine. It was also reported that the engine could work at 420 rpm at noon on a clear sky day in New York [36].

Meinel and Meinel [39] commented on the conclusions made by Ericsson pointing out that solar-powered engines would be economical only in remote areas where sunshine was available and pointing out their cost was 10 times higher than conventional engines. The amount of solar-powered Stirling engines built in the first era was quiet small. Reader and Hooper [40] reported that in 1908 a solar-powered Stirling engine was proposed for a water pumping system.

4.2. Solar-powered Stirling engines in the second era

During 1950–1955, Ghai and Khanna worked with an open cycle solar-powered Stirling engine using a parabolic collector in India [4,17,38]. The solar energy was focused on the metal engine head but they had problems with heat loss. Jordan and Ibele [35] described the 100 W solar-powered Stirling engine for water pumping. Ghai [41] pointed out the point of economy and technical simplicity of a solar-powered device eventhough its competitor was the internal combustion engine.

Later works [42–44] related to solar-powered Stirling engines and heat pipes were previously reviewed by Spencer [17]. Other works concerning the different varieties and arrangements of the cylinder and displacer including construction and operation of solar-powered Stirling engines [45–50] have been reported by Daniels [38]. More details of solar-powered Stirling engines can be found from Jordan and Ibele [35] and Jordan [50].

4.2.1. Stirling engines with transparent quartz window

Daniels [38] and Spencer [17] described many research works on solar-powered Stirling engines with transparent quartz windows and related works [15,51–55]. The problems of this engine could be with the heat transfer and fouling effects. However, Walpita [4] proposed a design for a solar receiver made from a spiral steel tube of 3.175 mm outside diameter for a solar- powered Stirling engine. The heat transfer from solar radiation to the working fluid was analyzed and an optimum heat transfer area was obtained.

4.2.2. Stirling engines with concentrating collector

The review work on a 15 W solar-powered Stirling engine with concentrating collector was described by Daniels [38]. Other works on Stirling engine with concentrating collectors [56–64] have been comprehensively reviewed by Spencer [17]. Ahmed et al. [65] reported briefly the operation of a 50 kW solar-powered Stirling engine for electricity production using a single membrane dish concentrator and hydrogen as a working gas. They described the problems of the tracking system due to errors in design and difficulties in starting during the winter season due to improper control part selection.

Childs et al. [66] presented an innovative concept to determine the cost-effectiveness of new approaches to solar-powered desalting technology. These approaches combined modern solar conversion technology with newly developed, hydraulic-driven pumping and energy recovery technology for solar-powered desalting. A solar dish concentrator-Stirling engine electric module, having overall efficiency of 22% for 10 h/day average production, was reported.

Audy et al. [67] reported a solar dynamic power system using a Stirling engine for space station applications. Theoretical models for four different representative orbit configurations were developed. The simulation results were compared to those of a solar dynamic power module using a Brayton gas turbine. Moreover, they showed that the complex unsteady behavior with either the Brayton cycle or Stirling cycle can be simplified on the basis of parameterizations and energy balances.

4.2.3. Solar dish/engine technology

Solar dish/engine systems convert solar energy to mechanical energy and then electrical energy. In order to obtain the required temperature for efficient energy conversion, solar dish/engine systems use a mirror array to track the sun. These systems can be characterized by efficiency, modularity, autonomous operation and the capability to work with either a conventional fuel or solar energy. Among many solar technologies, these systems have been accepted to be the systems with the highest solar-to-electrical conversion efficiency [68].

High-temperature and high-pressure Stirling engines working with hydrogen or helium are normally used in solar dish/Stirling system engines. Modern high performance Stirling engines usually operate with a working fluid temperature of over 973 K and a pressure as high as 200 bar. The efficiencies of conversion from heat to electricity of the best Stirling engines are about 40% [9,10,69]. At this moment the kinematic Stirling engines, the Kockums (United Stirling) 4-95 25-kW$_e$, Stirling

Thermal Motors STM 4-120 25-kW_e, and the SOLO 161 11-kW_e are the examples for the engines used for dish/Stirling systems.

Solar dish/engine technology is one of the oldest solar technologies. In the late 1970s and early 1980s modern solar dish/engine technology was developed by Advanco Corporation, United Stirling AB, McDonnell Douglas Aerospace Corporation (MDA), the US Department of Energy (DOE), and NASA's Jet Propulsion Laboratory.

It was reported that [68,70] the Advanco Vanguard system, 25-kW_e nominal output module, using the United Stirling Power Conversion Unit (PUC), obtained a solar-to-electric conversion efficiency of 29.4%. MDA attempted to commercialize a system consisting of their own designed dish and the United Stirling PCU. Before the program was cancelled in 1986, MDA produced eight prototype systems. The rights to the MDA hardware were sold later to Southern California Edison (SCE). In 1988, an annual efficiency of over 23% was expected to be obtained without outages [71–74].

The Dish/Stirling Joint Venture Program (DSJVP) was initiated in 1991 [75]. The aim of the program was to develop a 5–10-kW_e dish/Stirling system for applications in remote areas. The Utility Scale Joint Venture Program (USJVP) for 25-kW_e dish/engine system was started in late 1993 [76]. The comparably priced systems obtained by the lower-cost stretch-membrane design and its improved operational flexibility were projected by SAIC [77].

The Advanced Dish Development System (ADDS) project plan and technical approach were reported by Diver et al. [78]. The aims of the project were to develop and validate a 9-kW_e dish/Stirling solar power system for remote power markets. The system was composed of the WGAssociates solar concentrator and controls, and the SOLO 161 Stirling power conversion unit. The main system components, features, test results and project status were also reported.

Davenport et al. [79] reported the operational results and experiences from a prototype of the SunDish system at the Salt River Project (SRP). This project was executed through the cooperation of SRP, SAIC, STM, and DOE. The methane gas collected from a landfill was used as fuel when solar energy was not available. They also discussed the design changes and system improvements resulting from operation with the prototype of the SunDish system.

Davenport et al. [80] reported the operation of the second-generation of dish/Stirling power systems (SAIC/STM SunDish systems). Many improvements to both the engine and dish subsystems were made to increase reliability, to improve system performance, to simplify installation, and to correct problems encountered during operation. They reported that the power output was improved from below 20 kW in 1998 to over 23 kW in 2002. An instantaneous peak power of 23.3 kW and efficiency of 26% were observed.

4.3. Solar-powered Stirling engine optimization

When a solar collector system is used as a heat input source for power generation, the solar collector and working conditions giving the optimum values of the cost of the system and the optimum power output must be considered. Some theoretical

work to optimize solar-powered Stirling engine design was carried out by Umarov et al. [81,82], however the applications on the engine were not shown in the research papers.

Howell and Bannerot [6] determined the optimum value of the outlet temperature of the solar collector to maximize the work output of Carnot, Stirling, Ericsson, and Brayton cycle engines powered by a solar collector. Eldighidy et al. [83] optimized the conditions for maximum solar energy absorbed by a flat-plate collector used with a plane reflector. A simple flat-plate collector/flat-sheet reflector was analyzed completely. Later, Eldighily [84] theoretically investigated the optimum outlet temperatures of the solar collector for the maximum work output for an Otto air-standard cycle with ideal regeneration. This work may be applied to an air-standard Stirling cycle.

Gordon [85] examined the accuracy of the energetic optimization of solar-driven heat engines. The results were obtained for the two limiting cases of maximum efficiency and maximum power. Altfeld et al. [86,87] minimized the sum of exergy losses, including exergy losses by absorption of radiation at the absorber temperature level by maximizing the net exergy flow. The optimum designs of the absorbers and flow ducts were presented. Costea et al. [88] studied the effect of pressure losses and actual heat transfer on solar Stirling engine cycle performance. The results indicated that when the engine was operated at the optimum temperature, the real cycle efficiency was approximately half the ideal cycle efficiency.

Chen et al. [89] proposed a non-image focusing heliostat consisting of a number of grouped slave mirrors for solar-powered Stirling engines. An experiment with a low power Stirling engine was reported. They proposed that a solar-powered engine of 20–50 kW was most in demand and would be less costly under stationary conditions.

5. Development of LTD Stirling engines

Haneman [90] studied the possibility of using air with low temperature sources. An unusual engine, in which the exhaust heat was still sufficiently hot to be useful for other purposes, was constructed. In practice, such an engine would produce only little useful work relative to the collector system size, and would give little gain compared to the additional maintenance required [91].

A simply constructed low temperature heat engine modeled on the Stirling engine configurations was patented in 1983 by White [92]. White suggested improving performance by pressurizing the displacer chamber. Efficiencies were claimed to be around 30%, but this can be regarded as quite high for a low temperature engine. In 1984, O’Hare [93] patented a device passing cooled and heated streams of air through a heat exchanger for changing the pressure of air inside the bellows. The practical usefulness of this device was not shown in detail as in the case of Haneman’s work.

Kolin [5] experimented with a number of LTD Stirling engines, over a period of many years. In 1983, he presented a model that worked on a temperature difference

between the hot and cold ends of the displacer cylinder of as low as 15 °C. After Kolin published his work, Senft [2] made an in-depth study of the Ringbom engine and its derivatives, including the LTD engine. Senft's research in LTD Stirling engines resulted in the most interesting engine, which had an ultra-low temperature difference of 0.5 °C. It is very difficult to create any development better than this result. Senft's work [94] showed the principal motivation for Stirling and general heat engines, their target being to develop an engine operating with a temperature difference of 2 °C or lower.

Senft [3] described the design and testing of a small LTD Ringbom Stirling engine powered by a 60° conical reflector. He reported that the 60° test conical reflector producing a hot-end temperature of 93 °C under running conditions, worked very well.

6. Conclusions

This article describes a number of research works on the technology of Stirling engines, solar-powered Stirling engines, and LTD Stirling engines. The keys to the success of the Stirling engine are new materials and good heat transfer to the working fluid. Good heat transfer needs high mass flows, then a lower viscosity working fluid is used to reduce pumping losses, or higher pressure is used to reduce the required flow or the combination of both.

Current research and development efforts on solar-powered LTD Stirling engines show considerable promise for future applications. The Stirling engine efficiency may be low, but reliability is high and costs are low. Simplicity and reliability are key to a cost effective Stirling solar generator.

The aim of this study is to find a feasible solution which may lead to a preliminary conceptual design of a workable solar-powered LTD Stirling engine. Since this engine is designed for use in rural areas, the engine design should be as simple as possible. The most appropriate type of solar-powered Stirling engine would be the LTD Stirling engine. The engine design should be that of a gamma-configuration, double-acting, vertical, LTD Stirling engine.

Since, during two-thirds of the day, solar energy is not available, solar/fuel hybrids are needed. This engine should be powered both by solar energy and heat from any combustible material. A supporting structure, which allows positioning of the engine to be powered both by solar energy and combustion heat, is needed.

For solar operation, the reflector focuses the solar energy directly on a displacer hot-end external surface for subsequent transfer by conduction to the air inside the displacer cylinder. As this cover plate acts as the solar absorber and also the displacer cylinder head, it must be able to tolerate the effects of high maximum internal pressures and temperatures.

The solar radiation concentrates on the absorber, which are the absorber and also the displacer hot-end head. As the absorber receives solar power, it heats up, and passes the heat to the air inside the displacer cylinder. The air expands under the pressure generated by the heat and moves the power piston. The power piston turns the crankshaft developing useful mechanical power.

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References

[1] Stine WB. Stirling engines. In: Kreith F, editor. The CRC handbook of mechanical engineers. Boca Raton: CRC Press; 1998. p. 8-7–8-6.
[2] Van Arsdell BH. Stirling engines. In: Zumerchik J, editor. Macmillan encyclopedia of energy, vol. 3. Macmillan Reference USA; 2001. p. 1090–95.
[3] Senft JR. Ringbom Stirling engines. New York: Oxford University Press, 1993.
[4] Walpita SH. Development of the solar receiver for a small Stirling engine. In: Special study project report no. ET-83-1. Bangkok: Asian Institute of Technology; 1983.
[5] Rizzo JG. The Stirling engine manual. Somerset: Camden miniature steam services, 1997.
[6] Howell JR, Bannerot RB. Optimum solar collector operation for maximizing cycle work output. Sol Energy 1977;19:149–53.
[7] Schmidt G. Theorie der Lehmannschen calorischen maschine. Zeit Des Vereines deutsch Ing 1871;15(1-12):97–112.
[8] Martini WR. Stirling engine design manual. 2nd ed. NASA CR-168088; 1983.
[9] West CD. Principles and applications of Stirling engines. New York: Van Nostrand Reinhold, 1986.
[10] Walker G. Stirling engines. Oxford: Clarendon Press, 1980.
[11] Walker G. Elementary design guidelines for Stirling engines. In: Proceedings of the 14th Intersociety Energy Conversion Engineerng Conference, Paper 799230. Boston: American Chemical Society; 1979.
[12] West CD. Theoretical basis for the Beale number. In: Proceedings of the 16th Intersociety Energy Conversion Engineering Conference, Paper 819787. Atlanta: American Society of Mechanical Engineers; 1981.
[13] Senft JR. A simple derivation of the generalized Beale number. In: Proceedings of the 17th Intersociety Energy Conversion Engineerng Conference, Paper 829273. Los Angeles: Institute of Electrical and Electronic Engineers; 1982.
[14] West CD. A historical perspective on Stirling engine performance. In: Proceedings of the 23rd Intersociety Energy Conversion Engineering Conference, Paper 889004. Denver: American Society of Mechanical Engineers; 1988.
[15] Trayser DA, Eibling JA. A 50-Watts portable generator employing a solar-powered Stirling engine. Sol Energy 1967;11:153–9.
[16] Gupta RK, Deshpande AM, Brave KM. Development of 1 kW solar powered reciprocating engine for rural applications. In: International Solar Energy Congress, New Delhi. 1978. p. 2016–20.
[17] Spencer LC. A comprehensive review of small solar-powered heat engines: Part I.I. Research since 1950—"Conventional" engines up to 100 kW. Sol Energy 1989;43:197–210.
[18] Pearce JM, Al Zahawi BA, Auckland DW, Starr F. Electricity generation in the home: evaluation of single-house domestic combined heat and power. IEE Proc-A 1996;143:345–50.
[19] Prodesser E. Electricity production in rural villages with biomass Stirling engine. Renew Energ 1999;16:1049–52.
[20] Dixit DK, Ghodke SV. Renewable energy powered Stirling engines—a viable energy alternative. In: Sayigh AAM, editor. Renewable energy technology and the environment. Proceedings of the Second World Renewable Energy Congress, vol. 2. 1992. p. 934–8.
[21] Markman MA, Shmatok YI, Krasovkii VG. Experimental investigation of a low-power Stirling engine. Geliotekhnika 1983;19:19–24.
[22] Orunov B, Trukhov VS, Tursunbaev IA. Calculation of the parameters of a symmetrical rhombic drive for a single-cylinder Stirling engine. Geliotekhnika 1983;19:29–33.

[23] Abdalla S, Yacoub SH. Feasibility prediction of potable water production using waste heat from refuse incinerator hooked up at Stirling cycling machine. Desalination 1987;64:491–500.
[24] Nakajima N, Ogawa K, Fujimasa I. Study on microengines: miniaturizing Stirling engines for actuators. Sensor Actuator 1989;20:75–82.
[25] Aramtummaphon D. A study of the feasibility of using heat energy from producer gas for running stirling engine by steam as working Fluid. Master thesis, King Mongkut's University of technology Thonburi; 1996.
[26] Hirata K, Iwamoto S, Toda F, Hamaguchi K. Performance evaluation for a 100 W Stirling engine. In: Proceedings of Eighth International Stirling Engine Conference. 1997. p. 19–28.
[27] Costea M, Feidt M. The effect of the overall heat transfer coefficient variation on the optmal distribution of the heat transfer surface conductance or area in a Stirling engine. Energ Convers Manage 1998;39:1753–63.
[28] Wu F, Chen L, Wu C, Sun F. Optimum performance of irreversible Stirling engine with imperfect regeneration. Energ Convers Manage 1998;39:727–32.
[29] Wu F, Chen L, Sun F, Wu C, Zhu Y. Performance and optimization criteria for forward and reverse quantum Stirling cycles. Energ Convers Manage 1998;39:733–9.
[30] Wu F, Chen L, Sun F, Wu C. Finite-time exergoeconomic performance bound for a quantum Stirling engine. Int J Eng Sci 2000;38:239–47.
[31] Gu Z, Sato H, Feng X. Using supercritical heat recovery process in Stirling engines for high thermal efficiency. Appl Therm Eng 2001;21:1621–30.
[32] Winkler W, Lorenz H. Design studies of mobile applications with SOFC-heat engine modules. J Power Sources 2002;106:338–43.
[33] Hsu ST, Lin FY, Chiou JS. Heat-transfer aspects of Stirling power generation using incinerator waste energy. Renew Energ 2003;28:59–69.
[34] Ptrescu S, Costea M, Harman C, Florea T. Application of the direct method to irreversible Stirling cycles with finite speed. Int J Energ Res 2002;26:589–609.
[35] Jordan RC, Ibele WE. Mechanical energy from solar energy. In: Proceedings of the World Symposium on Applied Solar Energy, Phoenix. 1955. p. 81–101.
[36] Spencer LC. A comprehensive review of small solar-powered heat engines: Part I. A history of solar-powered devices up to 1950. Sol Energy 1989;43:191–6.
[37] Ericsson J. Sun power; the solar engine. Contributions to the Centennial Exhibition, Philadelphia: John Ericsson, 1870. p. 571–77.
[38] Daniels F. Direct use of the sun's energy. New Haven: Yale University Press, 1964.
[39] Meinel AB, Meinel MP. Applied solar energy: an introduction. Reading, MA: Addison-Wesley, 1976.
[40] Reader GT, Hooper C. Stirling engines. London: Cambridge University Press, 1983.
[41] Ghai ML. Small solar power plants. In: Daneils F, Duffie JA, editors. Solar energy research. London: Thames and Hudson; 1955. p. 81–4 [Section 4].
[42] Dunn PD. Solar powered pumps. Joint Conference: University of Reading and U. K. I.S.E.S.: Solar Energy in Agriculture; 1976. p. 55–7.
[43] Meijer RJ. STM4-120 Stirling engine for solar application. Abs. I.S.E.S, Solar World Congress, Hamburg; 1987. p. 2, 13, 16.
[44] Khanna ML. Studies on hot-air engine run with solar energy conducted at the National Physical Laboratory, New Delhi, and a critical review of its present status, Paper 7/14, I.S.E.S. Conference, Melbourne; 1970. p. 1–7.
[45] Finkelstein T. Generalized thermodynamic analysis of Stirling engines. American Society of Automotive Engineers, Paper 118 B. Annual Meeting; 1960.
[46] Finkelstein T. Cyclic processes in closed regenerative gas machines. American Society of Mechanical Engineers, Paper 61-SA-21. Annual Meeting; 1961.
[47] Finkelstein T. Conversion of solar radiation into power. American Society of Mechanical Engineers, Paper 61-WA-297. Annual Meeting; 1961.
[48] Farber EA. A closed cycle solar engine. In: Solar Energy Symposium. Gainesville: University of Florida; 1964.

[49] Farber EA. An open cycle solar engine. In: Solar Energy Symposium. Gainesville: University of Florida; 1964.
[50] Jordan RC. Conversion of solar to mechanical energy. In: Zarem AM, Erway DD, editors. Introduction to the utilization of solar energy. New York: McGraw-Hill; 1963. p. 125–52.
[51] Utz JA, Braun RA. Design and initial tests of a Stirling engine for solar energy applications. MS thesis, Mechanical Engineering Department, University of Wisconsin; 1960.
[52] Finkelstein T. Internally focussing solar power systems. American Society of Mechanical Engineers, Paper 61-WA-297. Annual Meeting; 1961.
[53] Gurtler RW. Optically driven solar engine. U.S. Patent; 1979. p. 4, 173, 123.
[54] Walker G, Kentfield J, Johnson E, Fauvel R, Srinivasen V. Coal-fired Stirling engines for railway locomotive and stationary applications. Proc Inst Mech Eng 1983;197:46.
[55] Hull PG, Hunt AJ. A reciprocating solar-heated engine utilizing direct absorption by small particles. J Sol Eng Trans ASME 1984;106:29–34.
[56] Holland MB. The Stirling engine—power plant of the future? Charter Mech Eng 1979;April:60–3.
[57] Pons RL, Fox RJ. A solar/Stirling total energy system. In: Sharing the Sun, Solar Technology in the 1970s Conference, Winnipeg. 1976. p. 77–91.
[58] Brown CT, Mackie PE, Neale DH. Advanced component research in the solar thermal program. In: Proceedings of the Solar World Congress, Perth. 1983. p. 1421–5.
[59] Marriott AT. Solar electric power from parabolic dishes. In: Proceedings of the Solar World Congress, Perth. 1983. p. 1438–43.
[60] Selcuk MK, Bowyer JM. Dish Stirling module performance analysis as evaluated from tests of various TBC concentrator/USAB engine configurations as the parabolic dish test site. Ext. Abst. Intersol '85, Montreal; 1985. p. 313.
[61] McGlaun MA. The LaJet energy large scale innovative solar concentrator study of wind loading effects. Abs., I.S.E.S. Solar World Congress, Hamburg; 1987. p. 2, 18, 15.
[62] Schlaich J. Solar power plants with a membrane concave mirror-50 kW. Abs., I.S.E.S. Solar World Congress, Hamburg; 1987. p. 2, 18, 16.
[63] Al-Rebaian A, Hansen J. 50 kW Solar concentrators with stirling generators—results of the first six mounts of operation in Saudi Arabia. Abs., I.S.E.S. Solar World Congress, Hamburg; 1987. p. 2, 13, 15.
[64] Leibowitz L, Hanseth E. Solar thermal technology-outlook the 80's. Mech Eng 1982;104:30–5.
[65] Ahmed A, Al-Agami M, Al-Garni M. Solar powered Stirling engine with a single membrane dish concentrator. In: Proceedings of the First World Renewable Energy Congress, Energy and the Environment, Reading, UK, September 23–28, vol. 2. 1990. p. 1202–7.
[66] Childs WD, Dabiri AE, Al-Hinai HA, Abdullah HA. VARI-RO solar-powered desalting technology. Desalination 1999;125:155–66.
[67] Audy Ch, Fischer M, Messerschmid EW. Nonsteady behaviour of solar dynamic power systems with Stirling cycle for space stations. Aerosp Sci Technol 1999;1:49–58.
[68] Washom B. Parabolic dish Stirling module development and test results. In: Proceedings of the IECEC, Paper No. 849516, San Francisco. 1984.
[69] Stine WB, Diver RP. A compendium of solar dish/Stirling technology. Sandia National Laboratories, Albuquerque, Report SAND93-7026 UC-236; 1994.
[70] Droher J, Squier S. Performance of the Vanguard solar dish-Stirling module. Electric Power Research Institute, Palo Alto, Report AP-4608; 1986.
[71] Lopez CW, Stone KW. Design and performance of the Southern California Edison Stirling dish. In: Proceedings of the 1992 ASME-JSES-KSES International Solar Energy Conference, Maui. 1992.
[72] Lopez CW, Stone KW. Design and performance of the Southern California Edison Stirling dish. Sandia National Laboratories, Albuquerque, Report SAND93-7098; 1993.
[73] Stone KW, Drubka RE. Impact of Stirling engine operational requirements on dish-Stirling system life cycle costs. In: Proceedings of the 1994 ASME Solar Energy Conference, San Francisco. 1994.
[74] Stone KW, Lopez CW, McAlister R. Economic performance of the SCE Stirling dish. In: Proceedings of the IECEC, Atlanta. 1993.
[75] Bean JR, Diver RB. The CPG 5-kWe dish/Stirling development program. In: Proceedings of the IECEC, San Diego, Paper No. 929181. 1992.

[76] Gallup DR, Mancini TR, Christensen J, Beninga K. The utility scale joint-venture program. In: Proceedings of the IECEC, Monterey, AIAA-94-3945-CP. 1994.
[77] Beninga K, Davenport R, Sellars J, Smith D, Johansson S. Performance results for the SAIC/STM prototype dish/Stirling systems. In: Proceedings of the 1997 ASME International Solar Energy Conference, Washington. 1997.
[78] Diver R, Andraka CE, Rawlinson KS, Goldberg V, Thomas G. The advanced dish development system project. In: Proceedings of the Solar Forum 2001, Technical paper. 2001.
[79] Davenport R, Mayette J, Forristall RE. The salt river project sundish/Stirling system. In: Proceedings of the ASME Solar Forum 2001, Washington. 2001.
[80] Davenport RL, Butler BL, Taylor R, Forristall R, Johansson S, Ulrich J et al. Operation of second-generation dish/Stirling power systems. In: Proceedings of the ASES 2002 Solar Conference, Reno. 2002.
[81] Umarov GY, Orunov BB, Klyuchevskii YE, Tursunbaev IA, Trukhov VS. Thermodynamic analysis and choice of optimal parameters of dynamic converter for solar energy plant. Geliotekhnika 1976;12:31–4.
[82] Umarov GY, Trukhov VS, Tursunbaev IA, Orunov BB. A method for optimizing heat exchangers of a stirling engine. Geliotekhnika 1976;12(6):18–23.
[83] Eldighidy SM, Taha IS, Darwish MA. Optimum conditions for maximum solar energy absorbed by flat plate collector augmented by plane reflector. In: Proceedings of the Energy Symposium (ISATED), Montreux, Swiss. 1979. p. 28–32.
[84] Eldighidy SM. Optimum outlet temperature of solar collector for maximum work output for an Otto air-standard cycle with ideal regeneration. Sol Energy 1993;51:175–82.
[85] Gordon JM. On optimized solar-driven heat engines. Sol Energy 1988;40:457–61.
[86] Altfeld K, Leiner W, Feebig M. Second law optimization of flat-plate air heaters. Part I: the concept of net exergy flow and the modeling of solar air heaters. Sol Energy 1988;41:127–32.
[87] Altfeld K, Leiner W, Feebig M. Second law optimization of flat-plate air heaters. Part II: results of optimization and analysis of sensibility to variations of operating conditions. Sol Energy 1988;41:127–32.
[88] Costea M, Petrescu S, Harman C. The effect of irreversibilities on solar Stirling engine cycle performance. Energ Convers Manage 1999;40:1723–31.
[89] Chen YT, Chong KK, Bligh TP, Chen LC, Yunus J, Kannan KS et al. Non-imaging, focusing heliostat. Sol Energy 2001;71:155–64.
[90] Haneman D. Theory and principles of low-temperature hot air engines fuelled by solar energy. Report Prepared for U.S. Atomic Energy Comm. Contract W-7405-Eng-48; 1975.
[91] Spencer LC. A comprehensive review of small solar-powered heat engines: Part III. Research since 1950-“unconventional” engines up to 100 kW. Sol Energy 1989;43:211–25.
[92] White EW. Solar heat engines, U.S. Patent; 1983. p. 4, 414, 814.
[93] O’Hare R. Convection powered solar engine, U.S. Patent; 1984. p. 4, 453, 382.
[94] Senft JR. An ultra low temperature differential Stirling engine. In: Proceedings of the Fifth International Stirling Engine Conference, Paper ISEC 91032, Dubrovnik, May. 1991.